DIGITAL 3D MAPPING OF ACTIVE FAULTS BENEATH SANTA MONICA BAY, BASIN MODELING, AND STRAIN PARTITIONING: COLLABORATIVE RESEARCH UCSB AND LDEO

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Principle Investigators: Christopher C. Sorlien
Institute for Crustal Studies, University of California, Santa Barbara, California, 93106
Leonardo Seeber, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York 10964
ICS Telephone (805)-893-8231, ICS FAX (805)-893-8649
Sorlien email: chris@crustal.ucsb.edu
Sorlien URL: www.crustal.ucsb.edu/~chris
Co-authors on the project: Kris Broderick, UCSB; Ray Sliter, USGS; Bill Normark, USGS; Mike Fisher, USGS; Marc Kamerling, Venoco Inc; Bruce Luyendyk, UCSB

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INVESTIGATIONS UNDERTAKEN

We used industry and USGS seismic reflection data controlled by well and seafloor data to map blind faults and also several other faults that reach to or close to the seafloor. This work covers the area south of the mainland coast from Palos Verdes Hills through the Malibu Coast to Port Hueneme, which we loosely call northern Santa Monica Bay (**Fig. 1**). The maps were constructed digitally, depth-converted, and provided to the SCEC Community Fault Model (**Fig. 2**). In addition to these fault maps and our previously mapped lower Pliocene horizon, digital maps on base Pliocene and of the late Pliocene top "Repetto" horizon have been completed over the whole area. A ~50 ka horizon is correlated from ODP site 1015 (Normark and McGann, 2003; Shipboard Scientific Party, 1997) through part of the study area. This stratigraphic control allowed changes in deformation through time to be studied. Simple modeling of dip-slip on blind faults was performed on cross sections. Details of the Santa Monica-Dume faults system and modeled slip on this fault system is discussed in our previous Final Technical Report (Sorlien et al., 2003). New mapping and stratigraphic correlation provides more information on connections between these faults and on subsidence of the footwall basin. Here, we focus on blind and seafloor faults farther south.

INTRODUCTION

Several destructive earthquakes that affected metropolitan Los Angeles have occurred on blind faults. Blind faults have been inferred in and around Los Angeles in order to explain folding of the shallow crust. The largest anticlinoria along the southern California margin and Borderland, including the one expressed as the Santa Monica Mountains and Northern Channel Islands, can extend 200 km along trend and 50 km across trend (Shaw and Suppe, 1994; Davis and Namson, 1994a, b; Seeber and Sorlien, 2000). Very large anticlinoria are associated with a blind component of slip on faults of equal or larger size. Blind thrusts have been imaged on seismic reflection data, one example being the Puente Hills thrust beneath northeast Los Angeles basin (Shaw and Shearer, 1999). The southwest margin of Los Angeles basin has been interpreted as a backlimb above a NE-dipping blind thrust ramp called the Compton-Los Alamitos thrust (Shaw and Suppe, 1996; see also Davis et al., 1989). While proposed slip rates on this fault are low (1.4 +/- 0.4 mm/yr; Shaw and Suppe, 1996), and its existence is controversial, recent earthquakes in southern California suggest that a failure on one or more of its segments would be devastating.

The Palos Verdes Hills are the surface expression of a NW-trending anticlinorium (Dibblee, 1999). The southwest limb of this fold was explained as a backlimb above a SW-dipping backthrust that forms the roof of a SW-directed tectonic wedge (Davis et al., 1989; Shaw and Suppe, 1996). The tip of this wedge is located beneath the deep San Pedro Basin in the interpretation of Davis et al. (1989). In this interpretation, the SW-dipping backthrust explains the entire SW-dipping limb that extends from Palos Verdes hills offshore beneath the San Pedro escarpment (**Fig. 3A**). Alternatively, the tip of the southwest-directed wedge is near the coastline does not explain the San Pedro escarpment in the interpretation of Shaw and Suppe (1996). Finally, it is possible to dispense with the backthrust altogether and still explain the entire onshore-offshore fold limb. Within our study area, we interpret the San Pedro escarpment to be a broad forelimb above a NE-dipping fault or fault system.

Structural highs extend offshore to the southeast and northwest of Palos Verdes Hills. The northwest extension has been called the Shelf Projection (**Figs. 3A,3B**; e.g., Nardin and Henyey,

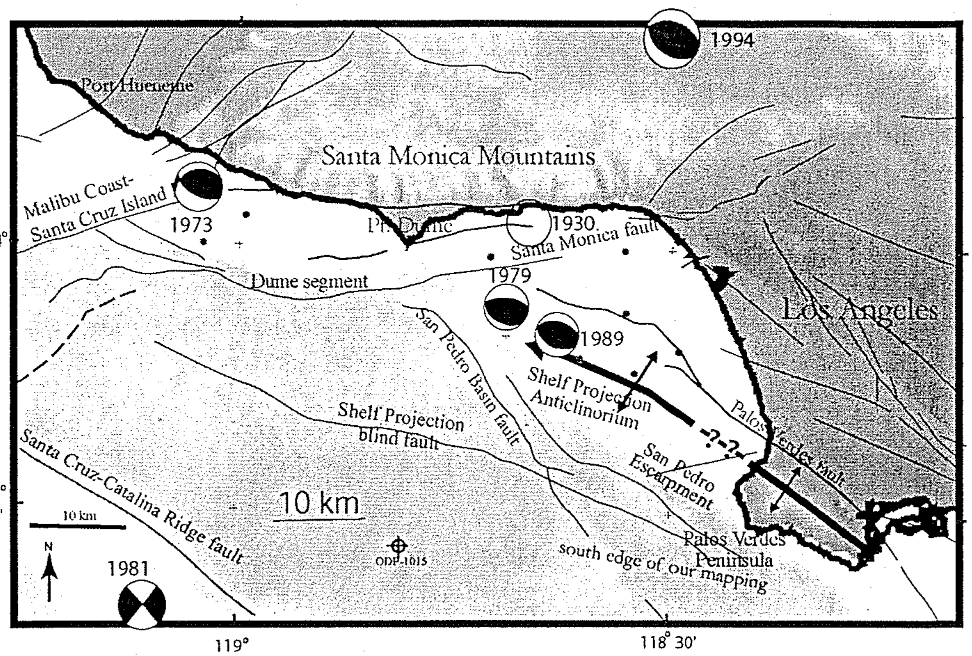


Figure 1: Fault map of Santa Monica Bay and vicinity. Focal mechanisms from USGS and SCEC (1994) and Haukkson and Saldivar (1986). Red dots are those wells used in the project (others exist). The Palos Verdes anticlinorium extends WNW beneath the Shelf Projection.

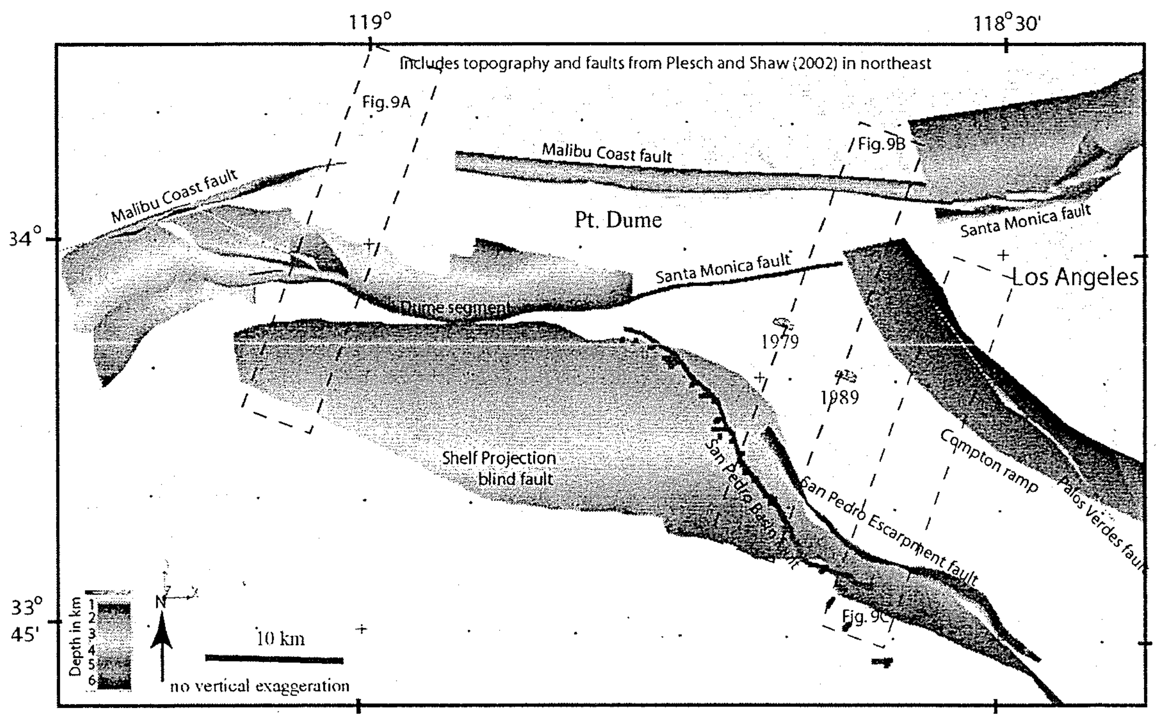


Figure 2: Map of fault surfaces. The onshore Malibu Coast fault, onshore Santa Monica Fault, Compton ramp, and Palos Verdes fault are from Plesch and Shaw (2002) and are made transparent below 6.5 km. The other faults were supplied by us to the SCEC CFM. The Southeast part of our Shelf Projection blind fault and the San Pedro escarpment fault are aligned in 3D with the Compton ramp. The offshore Santa Monica fault east of Point Dume dips moderately north; we did not map it to the coast due to a data gap.

1978) or Santa Monica Plateau (Gardner et al., 2003). The Shelf Projection is the bathymetric expression of the Shelf Projection anticlinorium (**Fig. 4**; Nardin and Henyey, 1978). This anticlinorium was interpreted to be en-echelon, right-stepping with the Palos Verdes anticlinorium and offshore folds farther southeast (Nardin and Henyey, 1978). Active folding of the Shelf Projection was interpreted to pre-date 1 Ma (Nardin and Henyey, 1978), but there has been much seismicity beneath the Shelf Projection, including M5.0 earthquakes in 1979 and 1989 (**Fig. 1**; Hauksson and Saldivar, 1986; Hauksson, 1990). We re-evaluate continuity of the anticlinoria, examine evidence for active folding, map the upper parts of underlying faults, and model long-term average slip rates and how these might relate to modern slip rates.

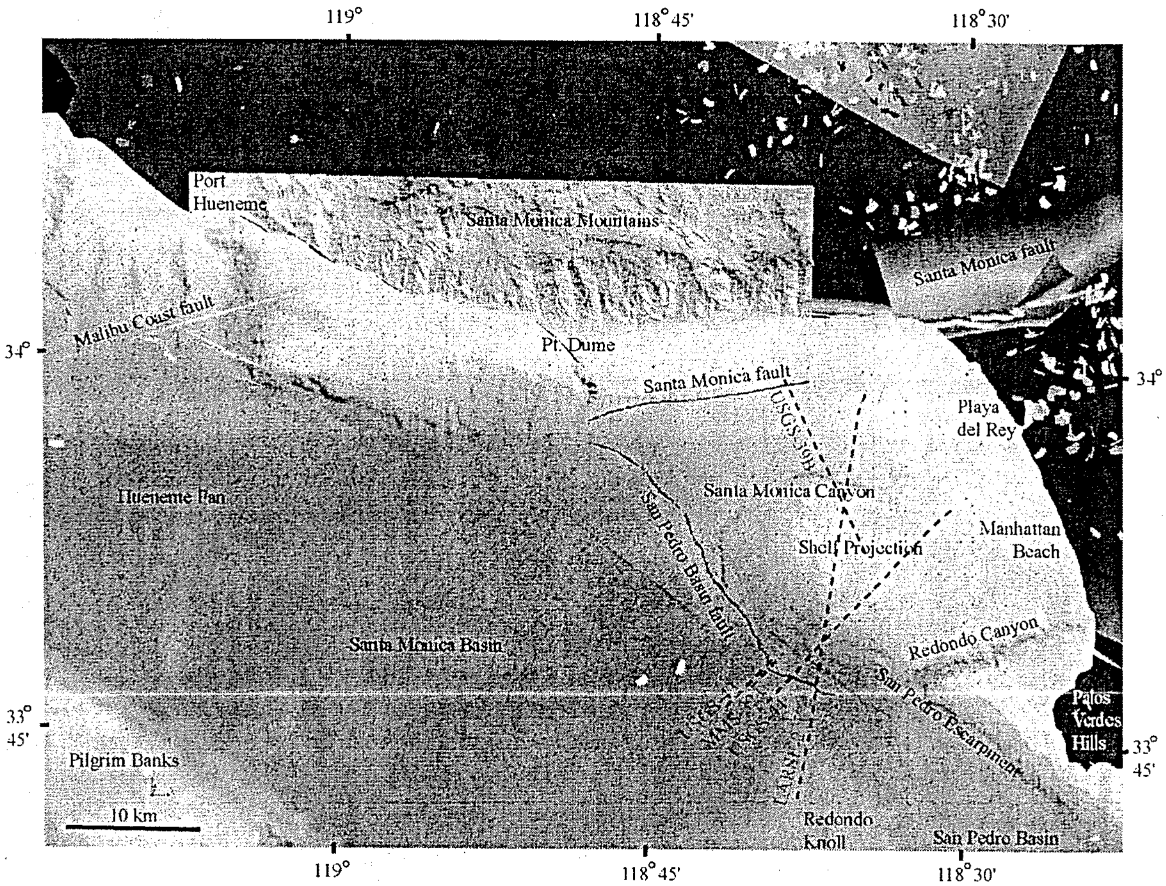


Fig. 3A: 3A-vertical view of bathymetry with no vertical exaggeration, a few seafloor faults from our mapping, and onshore faults from the SCEC CFM (Plesch and Shaw, 2002). Selected earthquake slip planes are shown through semi-transparent topography (Hauksson, 2000); part of the Santa Monica Mountains are shown as high-resolution and opaque. Faint grids of lines are part of the seismic reflection database that was used; profiles shown as labeled black dashed lines are the figures.

DATA, METHODS, AND MAPPING

Seismic Reflection Data

We used three different overlapping grids of industry multichannel seismic reflection data, and a few profiles from two other data sets to map structure in 3D and correlate stratigraphy through northern Santa Monica Bay (**Fig. 3A**, **Fig. 4 inset**). An additional 800 m x 2500 m grid of single-

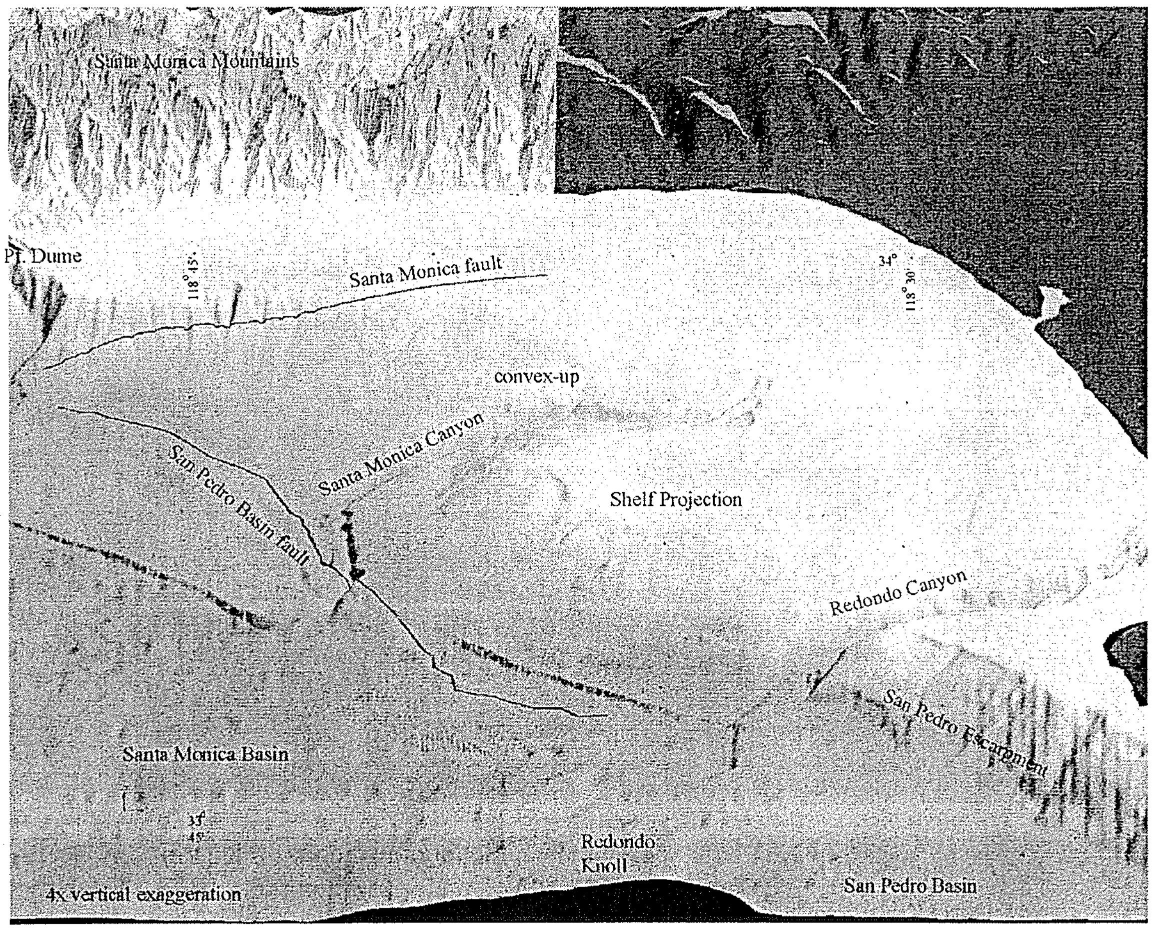


Figure 3B: Oblique view of bathymetry and topography at 4x vertical exaggeration. The sea floor trace of the Santa Monica fault was mapped using seismic reflection profiles; it coincides with disruptions of ravines. The area labeled "convex up" may be a northwest continuation of the Palos Verdes-Shelf Projection anticlinorium (see Gardner et al. 2003, for high-resolution bathymetric figures and cross sections). Santa Monica Canyon is more deeply entrenched in the "convex-up" area and near the San Pedro Basin fault.

channel sparker and minisparker reflection data was used to map part of the San Pedro Basin fault trace at the seafloor, and to correlate ODP-1015 stratigraphy (data described in Burdick and Richmond, 1982). Several multichannel profiles acquired by the USGS in 1998 and 1999 were redisplayed and four others were reprocessed (**Fig. 5**, Fisher et al., 2003; Bohannon et al., submitted). We interpreted most of the other 1998 and 1999 profiles at Menlo Park using an interactive system, with correlations made between these USGS profiles using paper prints of industry data.

Digital Mapping

The output data points from our mapping at USGS were provided as UTM-X-Y two-way travel time text files. These data were combined with data points from our interpretation of industry and MMS data, gridded, and then depth converted. This approach was used for the San Pedro Basin fault and all horizons and faults to its east, while elsewhere we digitized points from maps derived from paper prints of industry data. Digital gridded travel-time maps were converted to depth using 2 and 3 layered velocity models for the Pliocene horizon and the fault maps, respectively (water, velocity gradient 1 above map horizon, velocity gradient 2 below map horizon). Slopes of velocity gradients were calculated from sonic logs from wells, and from stacking velocities of sub-horizontal reflections used in processing the seismic reflection data. Spatially-variable velocity slopes were used west of the San Pedro Basin fault and a constant slope was used east of that fault.

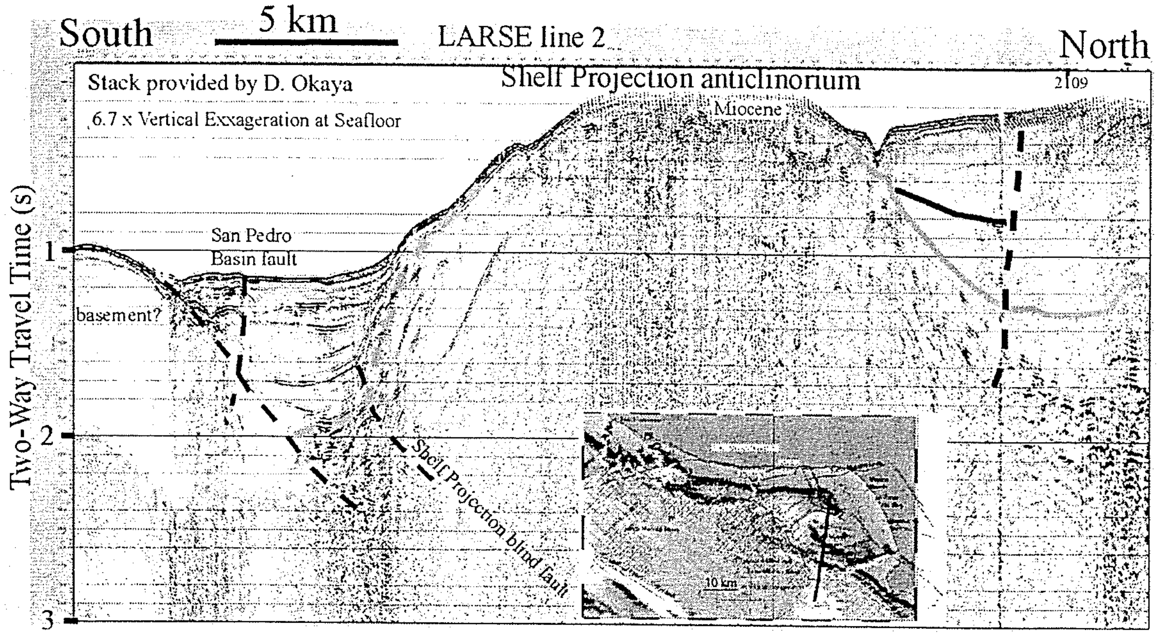


Figure 4: A stack of LARSE2, showing the anticlinorium, approximate top Miocene (green), top "Repetto" (brown), and NE-dipping Miocene normal-separation fault with probable Catalina schist in the footwall at Redondo Knoll (south end). San Pedro Escarpment fault not interpreted on this profile due to low resolution.

Seismic Processing

Several profiles were reprocessed at UCSB: USGS39B, 44, 48, and 103. The end result was not a migrated profile that was "better" than USGS processing; instead, we applied a special, somewhat radical approach to remove multiples. This involved a partial normal moveout (NMO) correction on shot gathers, FK-filtering of under-corrected reflections, and removal of the NMO correction. This was effective in removing multiples for profiles that were shot up the slope (towards the north or northeast) because the dip causes a delay for reflections to get to the far traces, in shot gathers. In the presence of dip in the opposite direction of ship travel, the apex of the hyperbolas is shifted ahead of the profile so that a more linear multiple reflection is recorded, making it susceptible to removal by FK filter (Mladen Nedimovic, oral communication, 2003). However, primary reflections with more than gentle south or southwest dips were also removed. None-the-less, in combination with standard processing, this approach allowed interpretation beneath the water bottom multiple, despite the short (250 m) streamer **(Fig. 5)**. A Finite Difference migration, output in depth and travel time, was applied to two profiles. A velocity model in layers, using realistic interval velocities from our experience in the region, was used for the depth migration, and for a time-to-depth conversion of an additional profile.

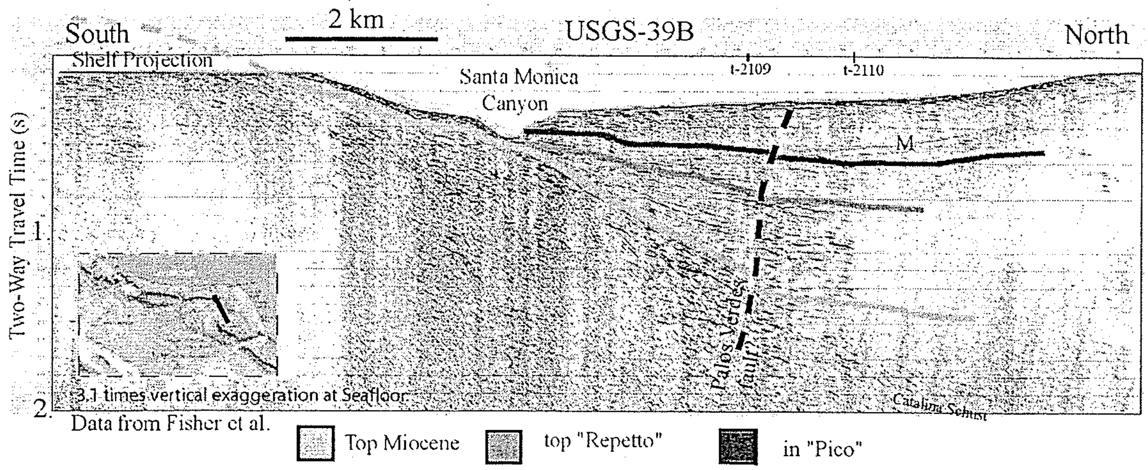


Figure 5: Our specially-processed stack across the north limb of the Palos Verde-Shelf Projection anticlinorium, where S-dipping multiples ("M"), and some steeper S-dipping primaries were removed, so that the progressive tilting of the strata is imaged. Located by the heavy black line in the inset and on Fig. 3A.

Stratigraphy and digital maps

Stratigraphic control was provided by logs from several wells drilled in the hanging-wall of the Dume fault, including 2 with sonic logs (**Fig. 2**). The well information was converted to travel time and correlated through the grids of reflection data, and around the east and west plunge of the Dume fault into the footwall basin to the south. Stratigraphic and paleontologic information from two wells constrain the interpretation in the basin between the Santa Monica fault and the Shelf Projection (**Fig. 5**). This correlation was supplemented by published information on seafloor outcrop (Vedder, 1990; Nardin and Henyey, 1978), by wells on the Shelf Projection, and by stratigraphic and velocity information from coastal and offshore oil fields at Playa del Rey and Venice Beach (Cal Div. Oil and Gas, 1992, Wright, 1991). Detailed stratigraphic information is also available in that area in a technical report (Davis and Namson, 2000). Finally, stratigraphic information for the last estimated 50 ka is available from ODP site 1015 (Shipboard Scientific Party, 1997; Normark and McGann, 2003). A reflection near the base of that hole, 150 m or 200 milliseconds (ms) two-way travel time (TWTT) below seafloor (bsf), has been correlated along several paths to the San Pedro Basin fault, to the southwest limb of the Palos Verdes-Shelf Projection anticlinorium, and across the San Pedro Escarpment fault (**Figs. 6, 7**).

We previously produced structure-contour maps for 36 km along strike of the Dume segment of the Santa Monica-Dume fault, and for 50 km along strike of a blind fault beneath and south of the Santa Monica-Dume fault (Sorlien et al., 2003a). We also mapped a horizon within the lower part of the Repetto rocks which was deposited before initiation of contractile folding, and which remains distinct from time-transgressive unconformities at the base and top Repetto interval over much of the area. This horizon does, however, locally onlap strata beneath, especially in the area south and east of Pt. Dume. We estimate that its age falls within the range for the base Repetto unconformity (between 4.42 +/- 0.57 m.y. and 3.4 +/- 0.3 m.y.; Blake, 1991). During the current project, we mapped additional faults, re-mapped the blind fault, and mapped the base Pliocene and top "Repetto" (~2.5 Ma, Blake, 1991) horizons. New fault maps include the offshore Malibu Coast fault, faults strands that connect the Dume segment to the Malibu Coast fault, a seafloor trace of the Santa Monica-Dume fault east of Point Dume (**Fig. 3b**), the San Pedro Basin fault (as 4 strands), and the southwestern strand of the San Pedro escarpment fault zone (**Fig. 2**). We also examined the offshore Palos Verdes fault, but decided that special reprocessing of the USGS data would be required to make sense of possibly several small strands (**Fig. 5**).

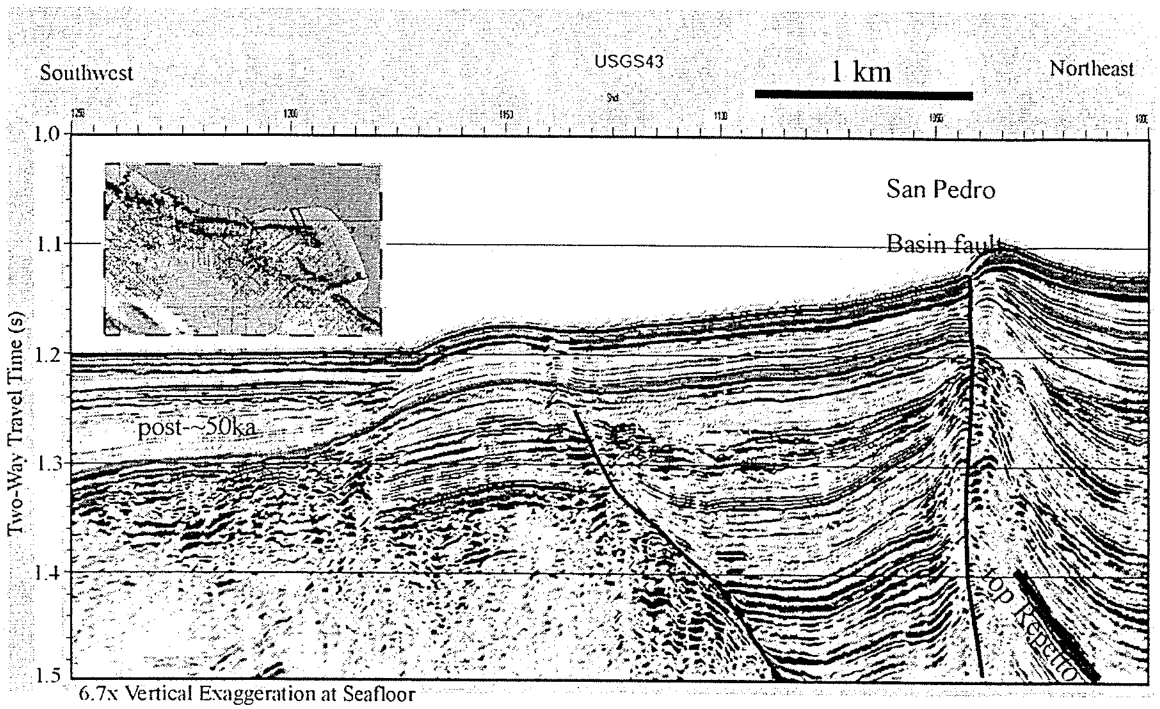


Figure 6: Migrated multichannel stack across a NE-dipping normal-separation fault, and the right-lateral San Pedro Basin fault. Located by heavy red line in inset and on Fig. 3A. The dark green horizon is the base of strata drilled at ODP site 1015. The top "Repetto" horizon is shown in brown. The reflective section below the post-50 ka strata at the southwest side may be Miocene or Pliocene.

Bathymetry and Three Dimensional Visualization

Having many different types of maps and data in the same 3D visualization system allows relationships between fault, folds, bathymetry, and seismicity to be evaluated. A digital database of geographically-registered 3D surfaces and objects was constructed using the software GOCAD (Mallett, 1992, 1997). This data base includes all of our maps of faults and stratigraphic horizons, trackline navigation of the seismic reflection data, 30 m digital elevation model (DEM) of the Santa Monica Mountains, lower resolution DEM from the SCEC Community Fault Model (CFM), faults from the CFM (Plesch and Shaw, 2002), seismicity, and bathymetry. Multibeam bathymetry, gridded at 16 m, are available for much of the study area east of Pt. Dume (Dartnell and Gardner, 1999). Eight meter resolution data in shallow areas were provided by P. Dartnell. In addition, we gridded NOAA point data for areas not covered by swath bathymetry, and combined this grid with the multibeam data, regridded at 60 m (shown in **Fig. 3**). **Figure 3b** shows that the seafloor trace of the Santa Monica fault coincides with disruptions of submarine ravines, and Santa Monica Canyon is more deeply entrenched near active faults and folds.

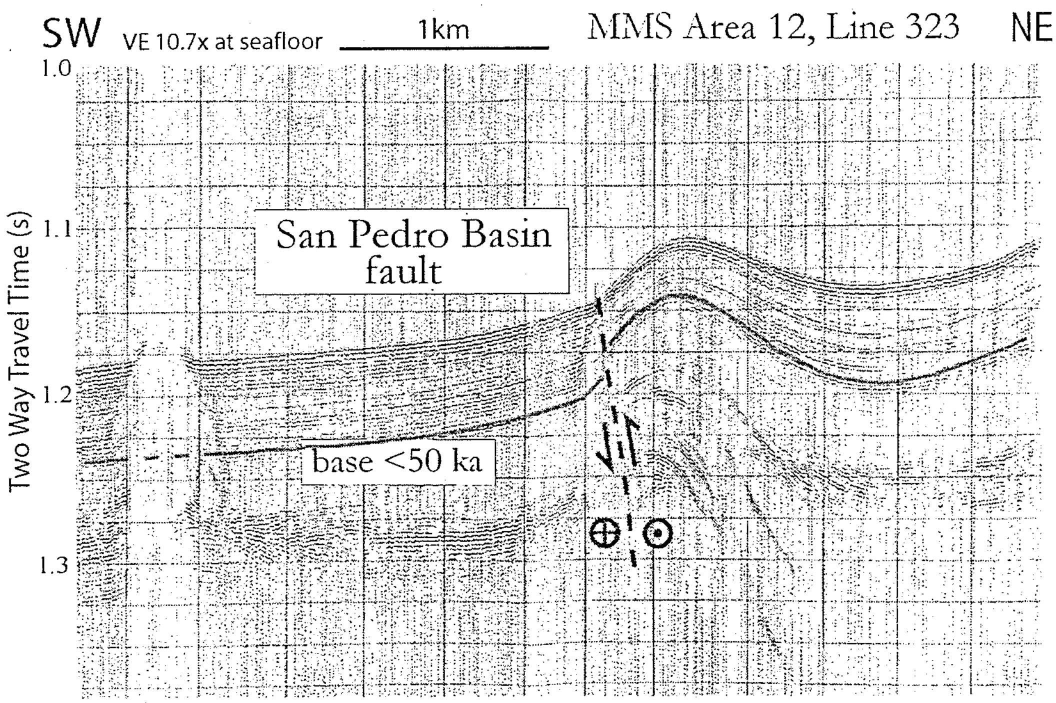


Figure 7: Minisparker profile MMS-323, located in Figure 3A, adjacent to USGS-43 (Fig. 6). Forty meters of relief since 50 ka is due to faulting, folding, and drape.

Seismicity

We previously created programs to convert precisely-relocated earthquake focal mechanisms (J. Armbruster) to GOCAD format, and imported 4714 of these for the Santa Monica-Los Angeles-San Fernando areas. For this project, we created an additional program to convert a standard earthquake format used by Hauksson (2000) to GOCAD format. For figures shown in this report, the Hauksson data are shown for years 1976 and 1981-2002, with the J. Armbruster and L. Seeber data for 1971, and for 1977-1980. Nodal planes are shown as polygons, and the slips as 3-D vectors (**Fig. 8**). The selected nodal plane and the slip of each side of each nodal plane can be displayed separately. Ten properties, including strike, dip, rake, and time, are included with each earthquake and the visualization can be limited to different ranges of these properties. The Armbruster-Seeber data have preferred nodal planes displayed, but the presumed arbitrary nodal plane is displayed for the Hauksson data.

INTERPRETATIONS

Faults

A blind N-dipping low-angle fault, the Shelf Projection blind fault, was re-mapped beneath central and eastern Santa Monica Bay, along 65 km of its strike (**Fig. 2**). We interpret it to be a basal Miocene detachment associated with clockwise vertical-axis rotation of the Santa Monica Mountains (see Kamerling and Luyendyk, 1979). It is located south of and beneath the Santa Monica-Dume fault (**Fig. 9a**). Several contractional structures indicate that it has been reactivated, with different structural styles for each. The western part, south and southwest of Pt. Dume, has been only slightly reactivated near its upper tip by post-Miocene folding. However, its downdip projection merges with or intersects the moderately-dipping Santa Monica-Dume fault. The central and southeast part of the fault projects beneath the WNW-trending Palos Verdes anticlinorium, including a 20 km-long offshore part beneath the Shelf Projection (**Figs. 1, 9b,c**). The post-Pliocene strata above the upper part of the fault, southwest of the San Pedro escarpment, exhibit little deformation (**Fig. 10**). Thus, while the mapped upper portion of the Shelf Projection blind fault (**Fig. 2**) may be inactive, the fault projects deeper beneath large anticlinoria and may be active at depth.

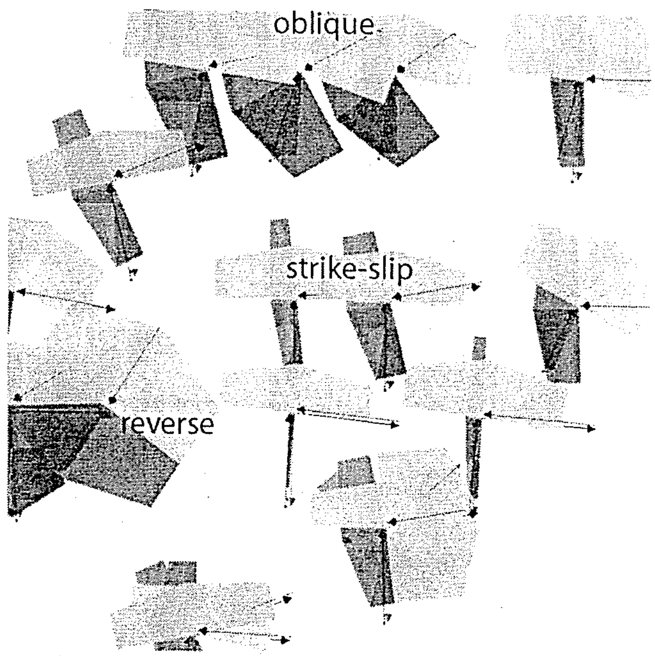
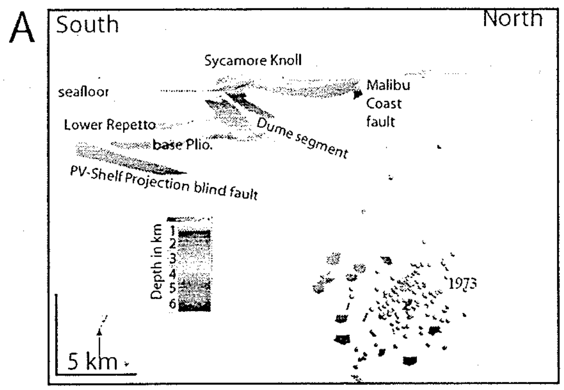
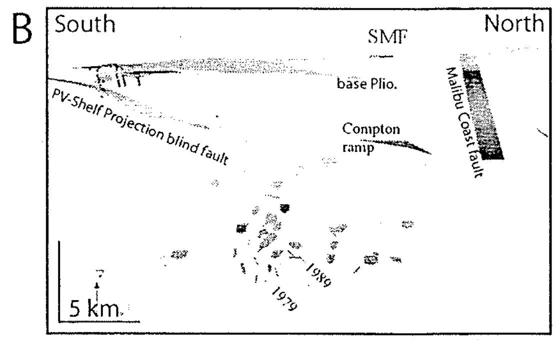


Figure 8: Our representation of earthquake nodal planes and slip using GOCAD. This view is straight down, with north to the top, and is of the Northridge aftershock zone. The chosen slip plane is red, the auxiliary plane is blue. Slip is shown for each side of each nodal plane. Several strike-slip mechanisms are shown in the center, a thrust is labeled, and oblique slip mechanisms are at the top.

We mapped a moderately NE-dipping fault near the base of the San Pedro escarpment in the hanging wall of the Shelf Projection blind fault (**Figs. 2, 10**). Faults along this trend have been called the San Pedro Escarpment fault zone (Nardin and Henyey, 1978; Bohannon et al., in press). Although we disagree with Bonannon et al. (in press) on the dip direction and sense of slip of the escarpment-forming fault zone, we retain the existing name. It is important to note that this fault extends along strike in both directions beyond where mapped, and so it is a larger earthquake source than what is shown in **Figure 2**. The strand of the San Pedro Escarpment fault that we mapped is the southwest edge of a narrow zone of faults. It dips northeast between 30° and 40°and thus converges downdip with the 20°-dipping Shelf Projection blind fault; they likely intersect at depth. Like the Dume segment of the Santa Monica fault (**Fig. 9a**), the San Pedro Escarpment fault may "cut off" slip on the deep fault, and may be an (oblique?) out-of-sequence thrust.

We cannot at this time tell whether the mapped strand of the San Pedro Escarpment fault flattens into the 20° dipping Shelf Projection blind fault, or if it continues at its 30° to 40° dip. Either way, both faults project downdip close enough to the Compton-Los Alamitos thrust ramp of Shaw and Suppe (1996; Plesch and Shaw, 2002) that they may be the updip part of that fault. This is especially possible given that the depth of the Compton ramp may be unconstrained in this area and its dip is based on a model.





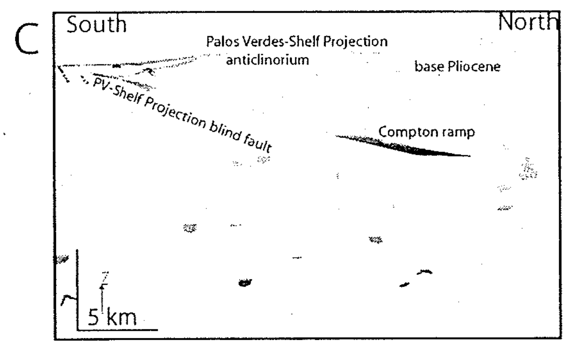


Figure 9: Five km-thick slices through GOCAD model, viewed towards 290 deg. azimuth, of one nodal plane from quakes from 1975-1976 and 1981-2002 (blue; Hauksson, 2000). Selected slip planes (red) from 1971 and 1977-1980 (Armbruster and Seeber). Slices located in Fig. 2. A: spheres are aftershocks of 1973 quake from Stierman and Ellsworth (1976). Legend gives depth of faults, base Pliocene is pink, ~4 Ma horizon within Pliocene is light blue. Nodal planes are polygons with point downdip and flat edge horizontal. B and C: Malibu Coast fault and Compton ramp from Plesch and Shaw (2002), shown to 6.5 km depth. Compton ramp aligned in 3D with Palos Verdes-Shelf Projection blind fault. SMF=trace Santa Monica fault.

The M5.0 1979 and 1989 earthquakes are spatially associated with the offshore part of the Palos Verdes-Shelf Projection anticlinorium. If the 20° dip of the Shelf Projection blind fault is projected into the Compton ramp as given by the CFM, these quakes, their aftershocks, and many other small quakes are beneath the fault (**Fig. 9**). If the variable 30° to 40° northeast dip of the San Pedro Escarpment fault strand is projected, the M5 quakes are beneath the fault but other quakes are near the fault. These quakes may be along and above a NE-dipping Miocene normal-separation fault whose seafloor trace is located farther to the southwest; we have little data across this fault and did not map it (**Figs. 4, 6**, see Larson, 2000). Relocated focal mechanisms of Hauksson (2000) and of Armbruster and Seeber do not show well-defined simple fault surfaces, although we have not focused our effort on interpreting the seismicity.

Basin Inversion and Basin Subsidence

Our new interpretation of the base Pliocene shows that the late Miocene section present in the hanging-wall of the Dume segment is not present in the footwall south of that fault. An angular unconformity separates the Pliocene strata from middle Miocene or older rocks. The regional and planar nature of this unconformity leads to the hypothesis that it was formed by wave erosion, and that beneath Hueneme Fan it has subsided as much as 4 km since the beginning of Pliocene time. This unconformity is time transgressive, as early Pliocene strata onlap or downlap onto it. The unconformity is as shallow as 1.5 km south of Point Dume. This does not necessarily mean a